Microtubes-An Enabling Technology in Numerous Fields

In recent years there has been great interest in miniaturization due to the high payoff involved. In the electronics field we have seen a dramatic decrease in device cost and a parallel increase in the reliability and the capabilities of these devices as they have become smaller. Currently, in other areas, such as microelectromechanical systems (MEMS) and the closely related fields of micro-fluidics and micro-optical systems, there is a desire to duplicate the miniaturization success in terms of cost, reliability, and capability that has taken place in the electronics field. In addition, there are also other drivers, such as system redundancy and weight savings in areas such as micro-satellites.

The vast majority of microdevices are presently made almost exclusively on planar surfaces using technology developed to fabricate integrated circuits. Although there have been numerous and very innovative successes using these silicon wafer-based technologies, there are some disadvantages. Since wafer technology requires the building-up of many layers of different materials as well as surface and bulk micro-machining, there are some very difficult material science problems to solve. In addition, for example, this technology is limited to relatively low use-temperatures and is limited in materials that can be used for fabrication. There are also problems associated with fluidic interconnect between wafers and with micro-devices such as coolers.

Microtube technology offers the possibility of truly 3-dimensional non-planar microsystems out of practically any material. In addition, microtube technology provides the opportunity to make microscopic tubing or channels of any configuration in order to miniaturize systems, connect components, and fabricate components or systems that are currently not possible to produce using wafer technology.

Commercially, tubing is extruded, drawn, pultruded, or rolled and welded. These techniques limit the types of materials that can be used for ultra-small tubes as well as their ultimate internal diameters. In addition, it is not currently possible to control wall thicknesses or inner surface finish to a fraction of a micron with these techniques. In contrast, our technology is able to produce tubes with smooth inner walls, a great diversity of axial and cross-sectional geometries as well as very accurately controlled wall thickness and composition. In addition, the Air Force Research Laboratory (AFRL) technology is able to produce microtubes with a much wider variety of materials than any other known process.

Like many other technologies, the AFRL approach employs a fugitive process using a sacrificial mandrel, which in this case is a fiber. By a proper choice of fiber, shape manipulation, coating composition, deposition method, and mandrel removal method,

tubes or channels of practically any shape and composition can be fabricated. Obviously, to make precision tubes of high quality, a great deal of material science is involved.

In contrast to tubing currently on the market, microtubes can be made from practically any material with precisely-controlled composition, diameter, and wall thickness in a great range of lengths. There is no upper diameter limit, and with practically any material, internal diameters of less than 5 microns are possible. In addition, for materials that can survive temperatures greater than 400°C, tubes can be made as small as 5 nanometers using the same process.

To date, tubes have been made from metals (copper, nickel, aluminum, gold, platinum, silver), ceramics (silicon carbide, carbon, silicon nitride, sapphire), glasses (silica), polymers (Teflon), alloys (stainless steel) and layered combinations (carbon/nickel, silver/sapphire) in sizes from 0.5 - 410 microns.

Since the process does not involve pultrusion, extrusion, rolling, or drawing but rather a very simple fugitive tube forming process, cross-sectional and axial shapes as well as wall thickness can be very accurately controlled to a fraction of a micron. A myriad of cross-sectional shapes with very uniform wall thicknesses have already been made as can be seen in Figure 1. These micrographs should be sufficient to demonstrate that practically any cross-sectional shape imagined can be fabricated.

The maximum length that these tubes can be made has yet to be determined because it depends on many variables, such as, type of tube material, composition of sacrificial tube forming material, degree of porosity in the wall, etc. It is possible that with a porous wall there is no limitation in length. For a non-porous wall the maximum length would probably be in the meter range with there being a direct relationship between the tube ID and the maximum possible length. However, for most applications conceived to date, the length need only be on the order of a few centimeters. If one does a quick calculation it is apparent that even "short" tubes have a tremendous aspect ratio. For instance, a 10 micron ID tube 1 inch long has an aspect ratio of 2500.

With microtube technology, there is virtually no limitation in wall thickness. To date, free-standing tubes have been made with wall thicknesses as small as 0.01 microns. These thin-walled tubes are very useful for insulation or composite reinforcement. Thicker walled tubes, which are just as easily fabricated, are needed in some applications, such as those involving pressure. Microtubes tested to date have demonstrated mechanical strength almost two times the tensile strength of an annealed wire of the same composition with the same cross-sectional area of material.

In addition to free-standing microtubes, solid monolithic structures with micro-channels can be fabricated by making the tube walls so thick that the space between the

tubes is filled (Figure 2). Alternatively, composite materials can be made using a material different ~~than~~ from the tube wall as a "matrix" that fills in the space between the tubes. The micro-channels in these structures can be randomly oriented or have any desired orientation or configuration of microtubes by using a fixturing process. The microtubes imbedded in these monolithic structures form micro-channels which, like free-standing tubes, can transport and contain solids, liquids and gases, as well as act as waveguides for all types of electromagnetic energy. In addition these tubes when placed in a solid structure can act as holes in the material, calibrated leaks, or lightweight structural reinforcement similar to that found in bone or wood. The cross-sectional shape of these reinforcement tubes can be tailored to maximize mechanical or other properties.

Besides being able to precisely control the tube wall thickness and composition, the interior surface of these tube walls can have practically any desired texture or degree of roughness. This control is highly advantageous and allows the use of microtubes in many diverse applications. For example, optical waveguides require very smooth walls while catalytic mixing-reactors would benefit from rough walls. (Because of the fabrication technique, the roughness on the interior of the tube wall can be quantified to a fraction of a micron.) Furthermore, depending on the application, the walls of microtubes can range from non-porous to extremely porous.

Another unique feature of microtube technology is the ability to coat the interior or exterior surface of these tubes with a layer or numerous layers of other materials (Figure 3). Alternating conductive and insulating layers would form a multiple-path conductor or a capacitor. A catalyst could be coated on the tube surface for chemical reactions. Other applications include using oxidation or corrosion protection layers on a structural tube material. In addition to layering, the tubes can be filled with another type of material to be used, for example, as a sensor or detector element.

Microtubes can be made straight or curved, or they can be coiled (Figure 4). Coiled tubes as small as 20 microns can be used, for example, as flexible connectors, or solenoid coils. For this later application, the coils could be of metal or of a high temperature superconductor with liquid nitrogen flowing through the tube. Another application for coils is for force or pressure measurement. In addition, a coiled spring tube wrapped around a core tube can be used as a counter-flow heat exchanger or as a screw-drive for micromachines.

Micro-bellows, like the coiled tubes, can be used as microscopic interconnects and can be made in practically any shape imaginable. Figure 5a shows a bellows with circular cross-section while the bellows in Figure 5b has a square cross-section with aligned bellows segments. If one end of the bellows is sealed, an entirely new group of applications become possible. That is, if a bellows end is sealed, the bellows can be extended, for example, with hydraulic or pneumatic means. In this configuration, a

bellows could be used as a positive displacement pump, a valve actuator, or for micro-manipulation.

A slightly more complex bellows is shown in Figure 5c. This is a tapered-square camera bellows with a circular sun shade to demonstrate the unique capability of this technology to produce various axial and cross-sectional geometries in the micron range from a variety of materials. In figure 5 d. a nozzle for a liquid rocket micro-thruster can be seen that demonstrates the capability of this technology to produce a smooth inner surface on a complex shaped object. Figure 5

For most applications it is necessary to be able to interface microtubes with the macro-world. This has been achieved in a number of ways. For example, a tapering process can be used in which the diameter is gradually decreased to micron dimensions. Alternatively, the tubes can be interfaced to the macro-world by telescoping or through numerous types of manifolding schemes.

Current, because of the small quantities involved, these tubes have been made by a batch process in the laboratory, but the technique is equally suited to a continuous process which would not only be more efficient but in some cases much easier. Obviously, a continuous process would reduce costs. For most materials these are already rather low because, unlike some other processes, expensive tooling is not required. For many materials such as quartz, aluminum, copper, etc. the cost is anticipated to be about \$0.01/cm. For precious metals such as gold or platinum, the cost would be significantly higher due to the cost of raw materials.

Microtubes appear to have almost universal application in areas as diverse as optics, electronics, medical technology, and microelectromechanical devices. Specific applications for microtubes are as diverse as chromatography, chemical micro-reactors, encapsulation, cross- and counter-flow heat exchange, injectors, micro-pipettes, dies, composite reinforcement, detectors, micropore filters, hollow insulation, displays, sensors, optical wave guides, flow control, pinpoint lubrication, micro-sponges, heat pipes, microprobes, plumbing for micromotors and refrigerators, etc. The technology works equally well for high and low temperature materials and appears feasible for all applications that have been conceived to date.

The advantage of microtube technology is that tubes can be fabricated inexpensively out of practically any material in a variety of cross-sectional and axial shapes in very precise diameters, compositions, and wall thicknesses that are orders of magnitude smaller than is now possible. In contrast to the other micro- and nano-tube technologies currently being developed, microtubes can be made from a greater range of materials with a greater range of lengths and diameters, and with far greater control over the cross-sectional shape. These tubes will provide the opportunity to miniaturize (even to nanoscale dimensions) numerous products and devices that are currently in existence as

well as allowing the fabrication of innovative new products that have to date been impossible to produce.

The intent of this article was to acquaint the reader with some of the basic capabilities of microtube technology and was not intended to be application specific. We are currently working with industrial and academic partners to develop application specific microtube technology through cooperative research and development agreements (CRDA). We welcome the opportunity to develop additional technology with future partners.

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FIGURE CAPTIONS

Figure 1. Above 1 micron inside diameter tubes can be made in any cross-sectional shape such as (a) 17 micron star, (b) 9 X 34 micron oval, (c) 59 micron "U", and (d) a 45 micron trilobal shape.

Figure 2. Solid nickel structure with oriented micro-channels.

Figure 3. Nickel tube with a silver liner.

Figure 4. Section of "large" coiled tube.

Figure 5. (a) A conventional round bellows. (b) A straight bellows with a square cross-section. (c) A tapered square camera bellows with a sun shade to demonstrate the versatility of the technique. (d) A miniature rocket nozzle for a micro-thruster.

Figure 1a

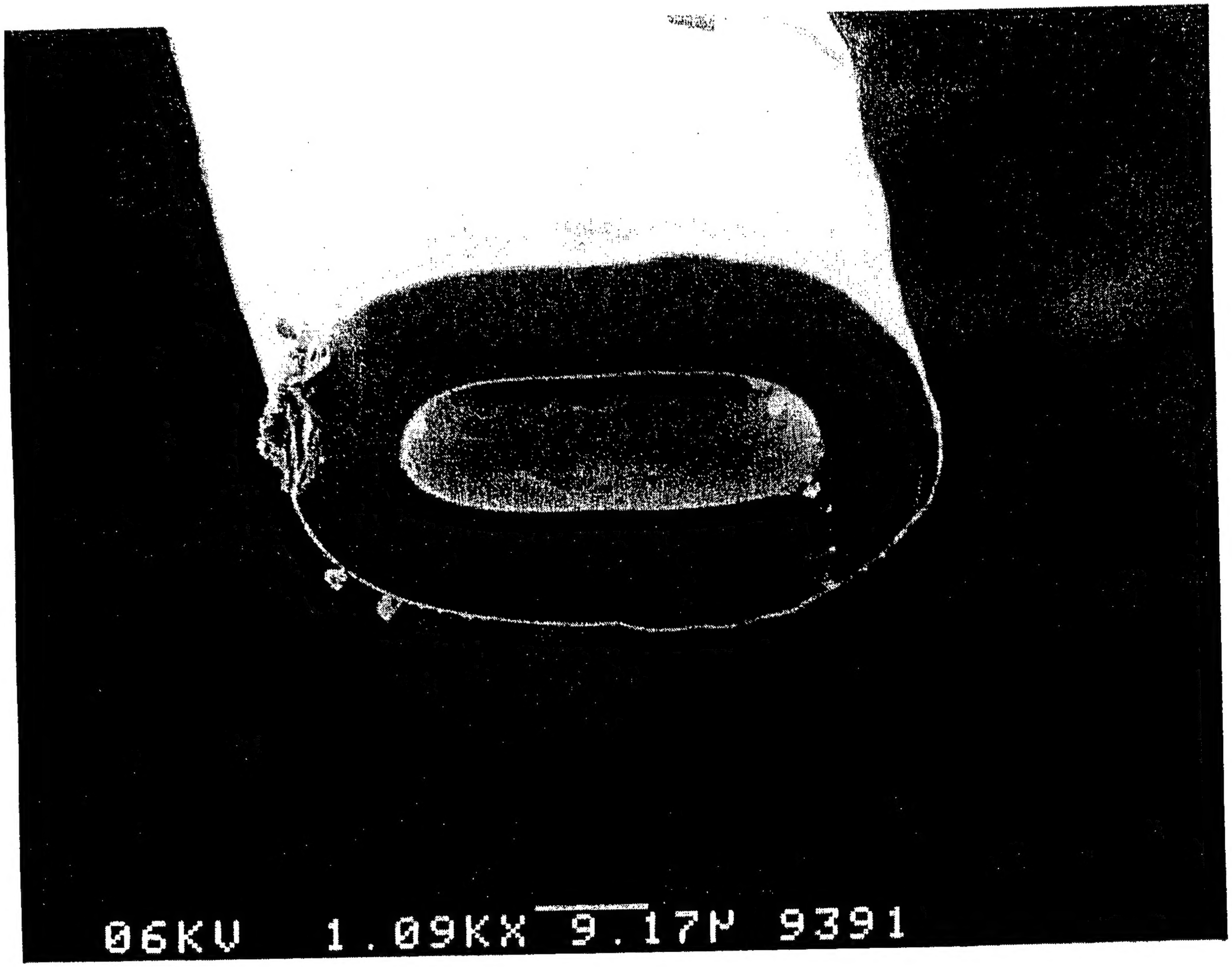


Figure 1b

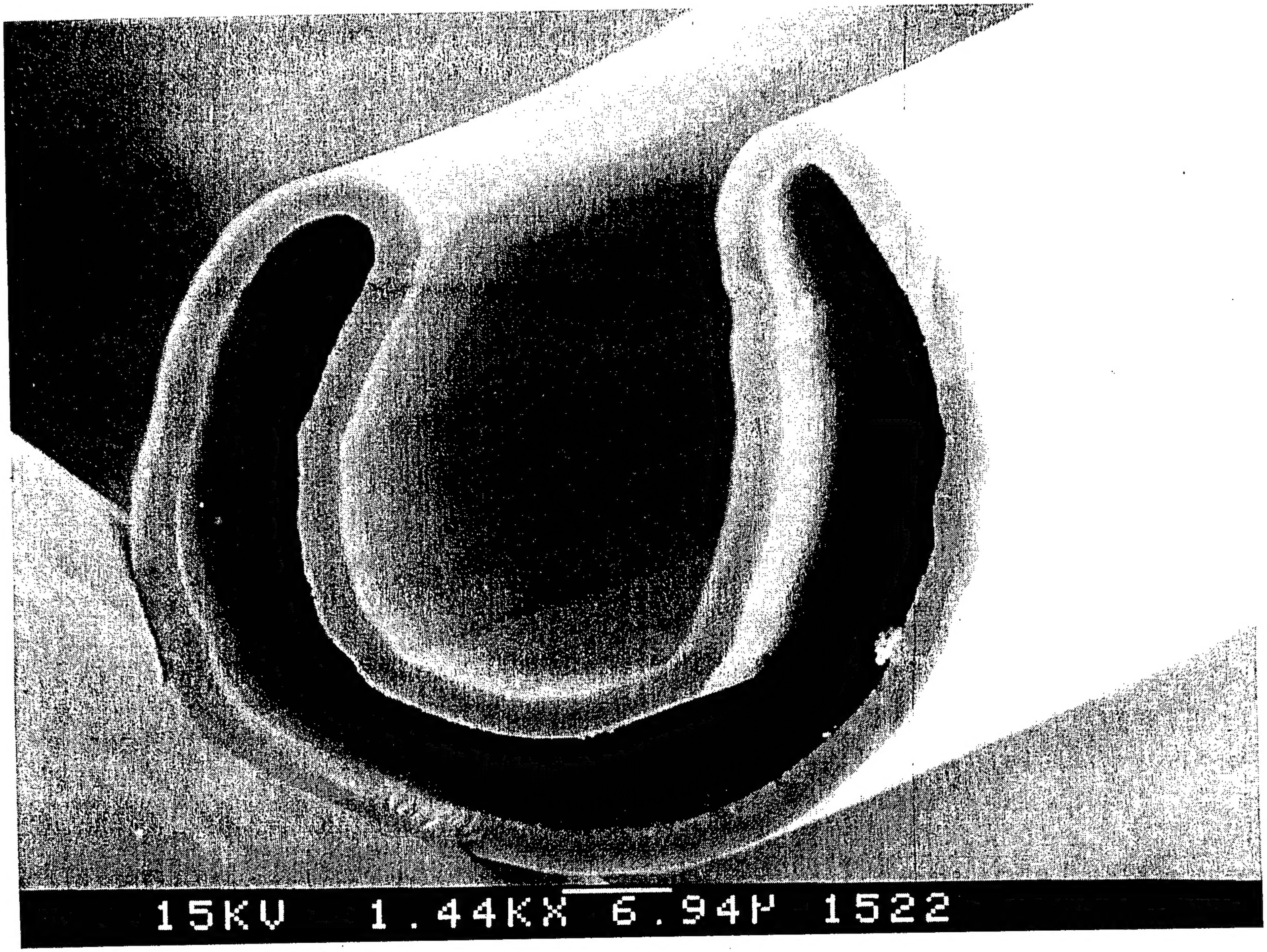
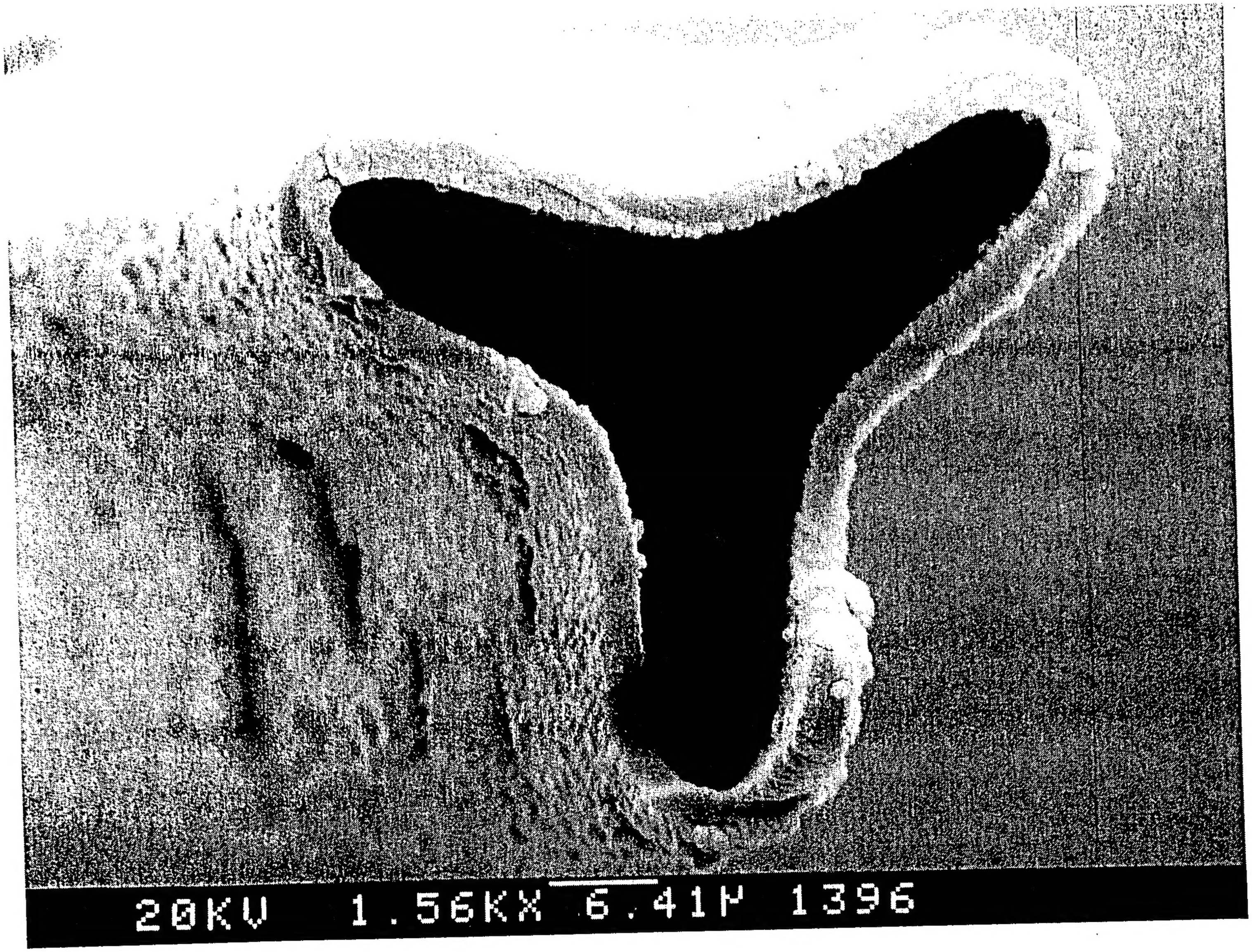


Figure 1c



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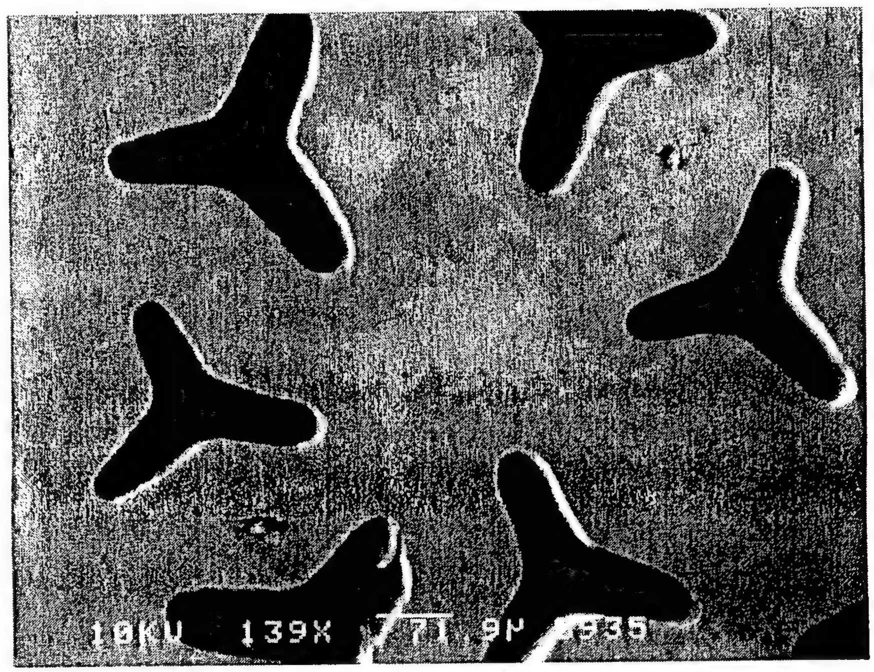
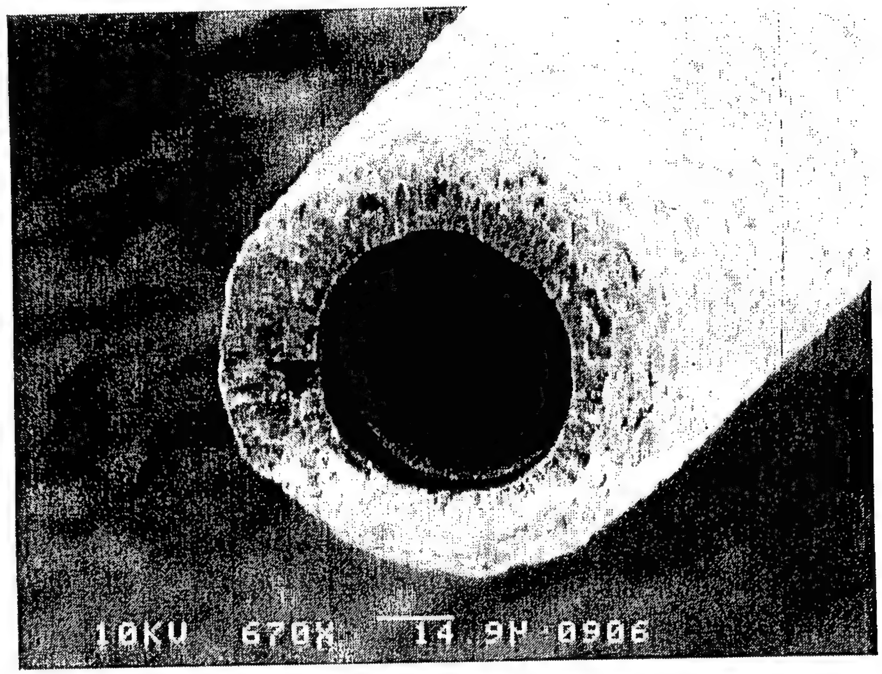


Figure 2



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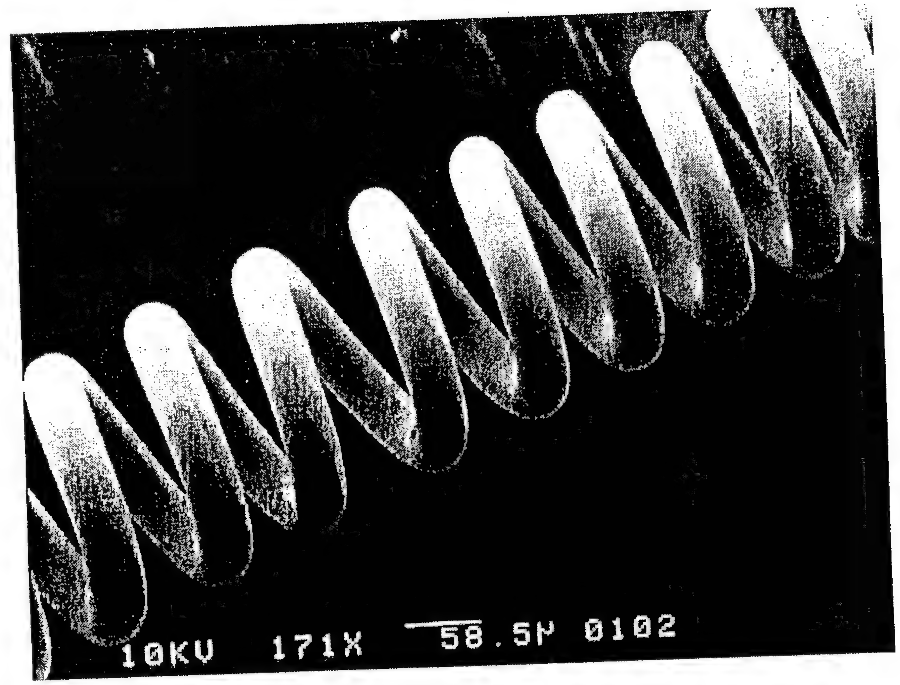


Figure 4

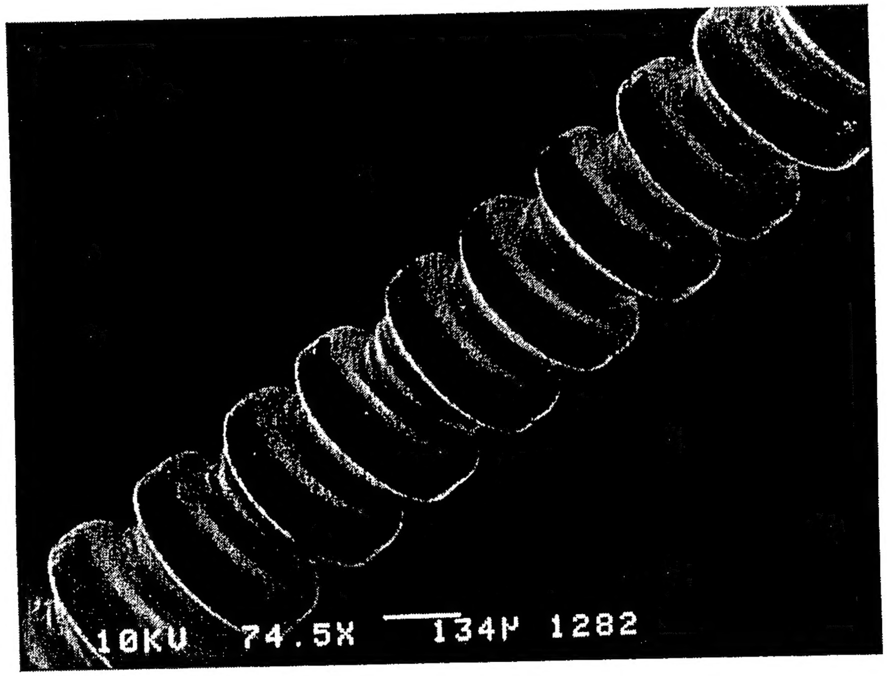
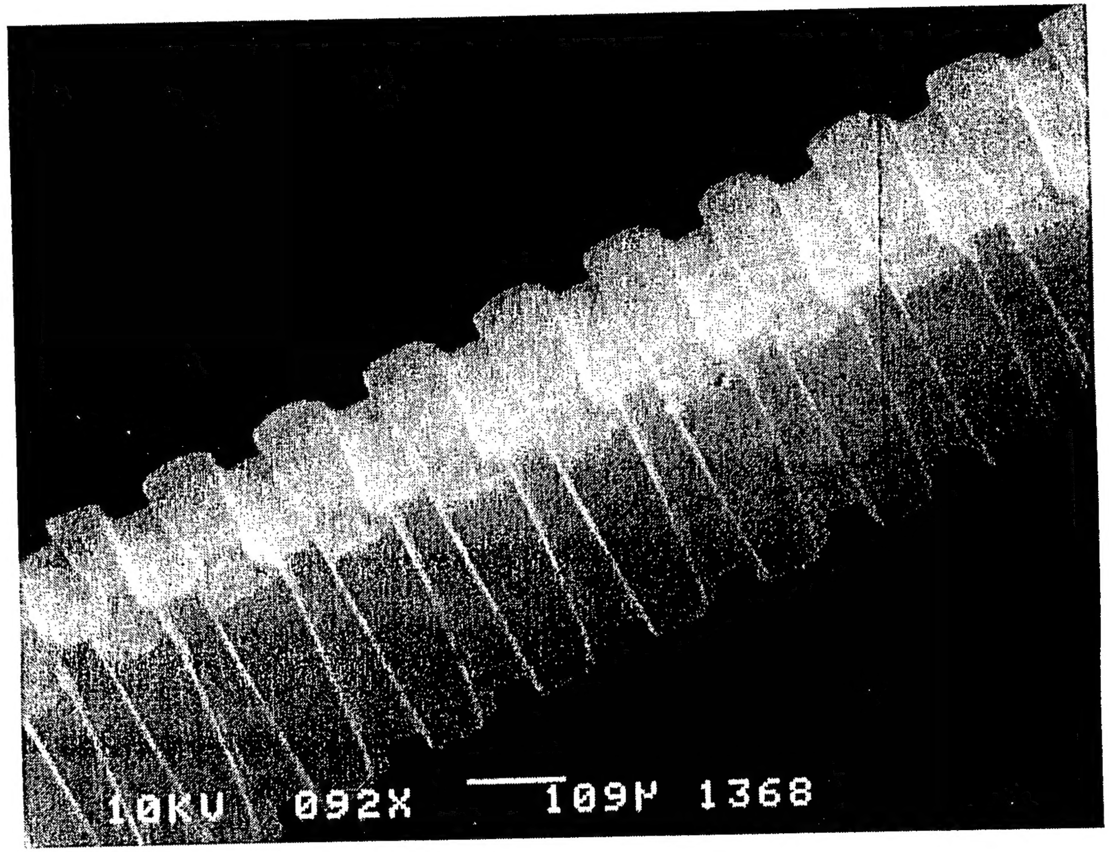


Figure 5a



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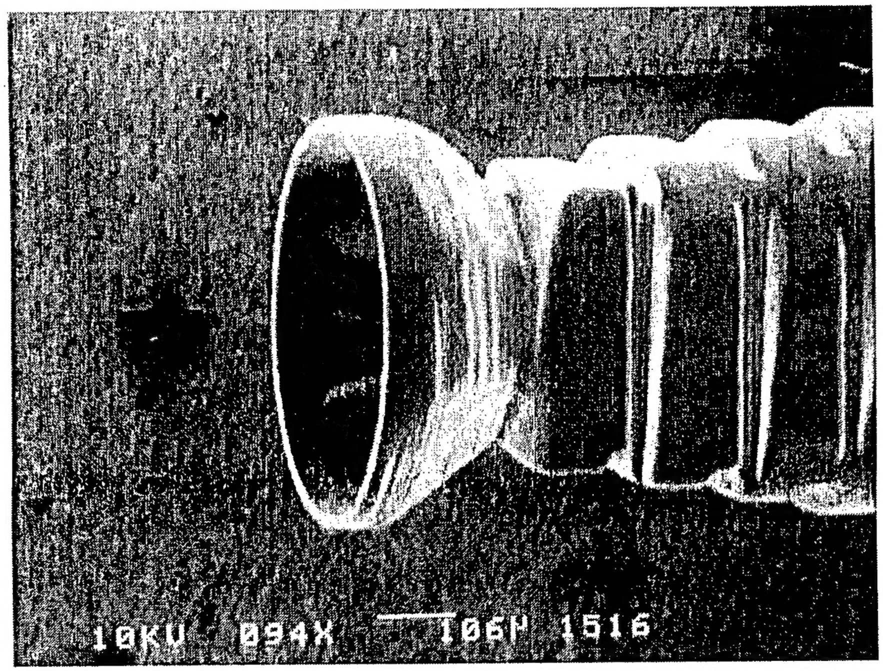

Figure 5c

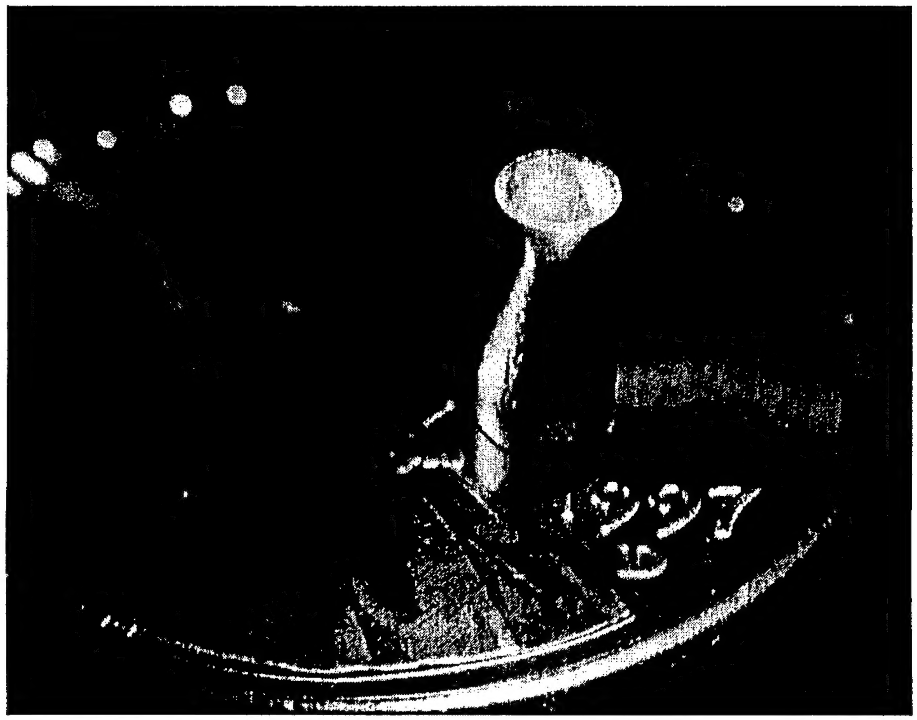

Figure 5d